A Study of Energy Budget at the Air-Ground Interface

MITSUTA, Yasushi; HANAFUSA, Tatsuo; TSUKAMOTO, Osamu; KAWANISHI, Hiroshi

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By Yasushi MITSUTA, Tatsuo HANAFUSA, Osamu TSUKAMOTO and Hiroshi KAWANISHI

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Abstract

Energy budget at the air-ground interface over bare soil on a fine summer day was studied by the direct measurement of each component. Net radiation and sensible and latent heat fluxes were measured at the height of about 2 m, and heat transfer into the ground was measured as the sum of the rate of time change of heat storage in the skin layer of the ground and heat conduction through the bottom of the skin layer. The results shows that, on the whole day, the net incoming radiation of 406 ly is balanced by the sensible heat flux of 79 ly, latent heat flux of 212 ly and heat transport into the ground of 107 ly. However, the energy budget in a short time period is not balanced, which may be caused by the underestimation of heat storage in the surface skin layer of the ground.

1. Introduction.

The aim of the present study is to clear the energy budget at the air-ground interface as a part of a series of experimental studies for the purpose of better understanding of atmospheric processes in the surface boundary layer.

The principle of conservation of energy states that all gains and losses of energy at the interface must balance. The conservation principle can be expressed as a very general equation applicable at any instant in time;

$$Q_N = Q_H + Q_E + Q_G, \tag{1}$$

where Q_N is the net all-wave radiation. A gain of energy by the interface is positive. Q_H is the turbulent transfer of sensible heat into the atmosphere, an upward flow being positive. Q_E is the contribution of latent heat of evaporation and evapo-transpiration. An upward flow of water vapor or evaporation is positive and a downward flow or condensation is negative. Q_G is the transfer of heat through the ground, a downward flow of heat being positive.

However, because of observational difficulties, it is not feasible to take measurements of energy fluxes exactly at the interface, and observations are usually taken a short distance from the interface in the study of micrometeorology. In this procedure, horizontal homogeneity and quasi-steadiness of the natural state are assumed. The contribution of latent heat of evaporation, Q_E is also represented by the turbulent transport of water vapor or latent heat flux above the surface. As the divergence of energy fluxes in the first one or two meters of boundary layer of the atmosphere within a properly chosen time length of sampling can be regarded to be negligibly small, the net radiation, Q_N, sensible heat flux, Q_H, and latent heat flux, Q_E can be measured at a height of one meter or so. While heat conduction into the ground at the interface, Q_G, is to be computed from the heat flux across a certain level underground surface and the time change rate of heat storage in the soil layer above that level, because heat capacity per a unit volume of soil is almost 10^3 times larger than that of air and heat storage, even in a thin layer of ground, cannot be disregarded.

Recent development of observational techniques for the direct measurement of turbulent fluxes enabled us to make continuous monitoring of the turbulent fluxes of sensible and latent heat in the surface layer, which had been one of the most difficult points in the observational studies of heat budget. Therefore, each term of the energy balance equation has become able to be directly evaluated, and we can examine contributions of all of the elemental processes of air-surface energy exchange and provide the background to the simpler method of turbulent flux estimate with indirect means, such as the heat balance method.

As is easily seen, the modified form of the energy balance equation does not hold good within a short time interval. It has been pointed out as the result of direct measurement of turbulent fluxes over water surface that the residue of the energy balance equation is appreciably large when the sampling duration is as short as five minutes, and it decreases with increasing sampling duration (Sahashi, 1967[1]). It is also reported that energy budget is balanced on a one day time base within an error of ten percent over bare soil (Hanafusa, 1971[2]).

The present study was planned to make the detailed observational analysis of energy budget over the bare soil surface, by the use of instrumentations developed by the present authors.

2. Experimental details

The experiment was taken on the testing site of the Shionomisaki Wind Effect Laboratory of the Disaster Prevention Research Institute, Kyoto University, on which the preliminary observations of the turbulent fluxes and heat budget were made (Mitsuta *et al*, 1970[3] and Hanafusa, 1972[2]). The ground surface of the site is bare soil which has been unchanged since the first experiment. The details of the site can be seen in the previous papers. The present experiment was made in the summer of 1972, and the continuous records of the fluxes and related parameters for one day long from 00:00 JST to 24:00 of July 14, 1972 were analyzed and discussed in this paper. The weather was clear all that day.

Net radiation, Q_N, was measured with a ventilated net radiometer supplied by Beckmann & Whitly Inc, installed at the height of 1.5 m from the ground. This instrument was calibrated by the reference instrument of the same type of Prof. Seo of Okayama University by intercomparison immediately after the experiment. The output was sampled and digitized with the rate of one sample per a minute and averaged over every thirty minutes of sampling.

Vertical turbulent transports of sensible and latent heat, Q_H and Q_E, were observed by the use of the combination of a three dimensional sonic anemometer-thermometer developed by one of the present authors (Mitsuta 1966[4]) and a fine wire thermocouple psychrometer (Sano and Mitsuta 1968[5]), together with momentum transport. The psychrometer was built in the wind antenna of the sonic anemometer-thermometer which was installed at the height of 1.9 m from the ground surface. The sound path length of the sonic anemometer-thermometer is 20 cm. The frequency response of the psychrometer shows more than 90% amplitude gain for the humidity fluctuation of 0.4 Hz or lower in the 5 m/sec wind at 20°C. To make the temperature response of the sensor compatible with that of humidity, the output of the dry-bulb temperature of the thermocouple psychometer was used for the air temperature signal instead of the temperature output of the sonic anemometer-thermometer. The specific humidity was computed after the simplified method presented by one of the present authors (Hanafusa, 1970[6]).

The turbulent fluxes were obtained by the eddy correlation method as,

$$
\begin{aligned}
Q_H &= C_p\overline{T'(\rho w)'} \\
Q_E &= L\overline{q'(\rho w)'} \\
M &= -\overline{u'(\rho w)'}
\end{aligned}
\tag{2}
$$

where C_p is specific heat of air, T air temperature, (ρw) vertical component of mass flow directly obtained by the sonic anemometer-thermometer, L latent heat of evaporation, q specific humidity, M momentum flux, u being the wind velocity component along the mean wind. The prime in this equation denotes the deviation of the entity from the mean value over the total sampling period of thirty minutes and the bar means the time mean over the sampling duration.

The data processing was made on site near real time base by the use of a data processing system (HYSAT) developed also by one of the present authors (Hanafusa 1971[7]). This system is a hybrid analog-digital computer which computes means, rms's and cross products of the singals in analog form and integrates to obtain the time mean value in digital form. In the present observation, the turbulent fluxes are obtained at every thirty minutes continuously.

The transfer of heat through the ground, Q_G, is obtained by the following relation

Table 1. Physical properties of soil at the depth of 2 cm.
Shionomisaki, July 14, 1972.

Time	Thermal Conductivity k(cal/cm^{2}sec °C)	Specific Heat $c\rho$(cal/cm^3 °C)	Water Content (g/cm^3)
00:00	3.6×10^{-3}	0.68	0.32
11:00	3.6×10^{-3}	0.68	0.32
17:00	3.3×10^{-3}	0.66	0.30
24:00	2.9×10^{-3}	0.62	0.26

Table 2. The results of observation of fluxes and related

Time	Momentum Flux	Net Radiation	Sensible Heat Flux	Latent Heat Flux	Heat Transport into the ground	Time Change of Heat Storage	Heat Conduction	Mean Wind Speed	Standard	
	M	Q_N	Q_H	Q_E	Q_G	$c\rho s \frac{\partial\theta}{\partial t}\Big\|_{\frac{z}{2}}$	$-k\frac{\Delta\theta}{\Delta z}\Big\|_z$	U	σ_u	σ_v
14th July 1972	(dynes/cm²)	(mly/sec)	(mly/sec)	(mly/sec)	(mly/sec)	(mly/sec)	(mly/sec)	(cm/sec)	(cm/sec)	(cm/sec)
00:00-00:30	0.12	−1.27	−0.33	0.52	−1.04	−0.23	−0.81	66	23	32
00:30-01:00	0.05	−1.35	−0.77	0.47	−1.04	−0.14	−0.90	73	21	18
01:00-01:30	0.09	−1.38	−0.21	0.32	−0.84	−0.08	−0.81	67	19	30
01:30-02:00	0.10	−1.31	−0.33	0.41	−0.89	−0.08	−0.81	67	29	19
02:00-02:30	0.05	−1.29	−0.39	−0.55	−0.74	−0.11	−0.63	79	20	16
02:30-03:00	0.26	−1.29	−0.22	0.34	−0.95	−0.14	−0.81	75	25	37
03:00-03:30	0.11	−1.38	−0.33	−0.26	−0.89	−0.08	−0.81	73	20	26
03:30-04:00	0.35	−1.31	−0.24	−0.15	−0.74	−0.11	−0.63	90	24	38
04:00-04:30	0.65	−1.23	−0.31	1.08	−1.13	−0.14	−0.99	103	35	63
04:30-05:00	0.67	−1.00	−0.40	−0.38	−1.16	−0.08	−1.08	151	49	82
05:00-05:30	0.46	−0.52	−0.28	−0.72	−0.90	0.00	−0.90	125	35	57
05:30-06:00	0.79	0.23	0.01	0.53	−0.61	0.11	−0.72	139	46	78
06:00-06:30	1.91	1.63	−0.28	0.87	−0.59	0.23	−0.72	189	46	80
06:30-07:00	0.57	2.83	−0.22	−0.88	−0.21	0.42	−0.63	187	38	67
07:00-07:30	0.45	5.71	1.10	1.23	0.23	0.68	−0.45	185	38	66
07:30-08:00	0.70	7.63	0.57	2.98	2.34	0.72	1.62	190	44	77
08:00-08:30	0.30	8.10	0.73	2.40	3.27	0.83	2.44	189	41	72
08:30-09:00	1.20	10.23	2.55	2.86	3.94	0.98	2.96	141	57	93
09:00-09:30	1.02	12.69	4.04	−0.04	4.92	1.06	3.86	154	72	95
09:30-10:00	1.14	14.31	4.59	1.10	5.81	0.87	4.94	145	129	131
10:00-10:30	2.19	15.27	3.91	−2.11	5.56	0.80	4.76	237	116	109
10:30-11:00	2.59	16.02	2.59	−0.48	6.77	0.87	5.92	252	112	81
11:00-11:30	1.81	16.71	3.42	3.14	7.06	0.68	6.38	223	107	96
11:30-12:00	1.59	16.50	3.30	−0.80	6.91	0.61	6.30	207	103	97
12:00-12:30	2.50	16.29	2.73	2.70	6.67	0.22	6.45	209	99	118
12:30-13:00	1.46	16.00	2.25	2.04	6.43	0.18	6.35	243	107	85
13:00-13:30	3.35	15.92	2.87	5.74	6.34	0.04	6.30	241	122	118
13:30-14:00	3.08	14.73	1.45	4.07	5.64	−0.18	5.82	231	119	114
14:00-14:30	3.75	13.48	2.77	6.59	4.76	−0.30	5.06	222	109	122
14:30-15:00	3.69	12.17	2.30	8.61	3.95	−0.30	4.25	193	103	129
15:00-15:30	2.85	10.75	2.74	3.32	2.97	−0.55	3.52	237	122	95
15:30-16:00	3.05	9.02	2.06	4.37	1.92	−0.78	2.70	198	88	139
16:00-16:30	3.06	6.71	0.96	9.42	0.30	−0.89	1.19	187	95	113
16:30-17:00	2.50	3.40	0.18	5.53	−0.21	−0.89	0.68	201	94	113
17:00-17:30	2.03	2.69	0.55	6.71	−1.06	−0.81	−0.25	197	65	113
17:30-18:00	1.07	1.13	−0.18	4.33	−0.94	−0.51	−0.43	195	58	94
18:00-18:30	1.80	−0.42	−0.31	5.37	−1.07	−0.59	−0.48	180	69	82
18:30-19:00	1.32	−1.54	−0.40	1.75	−1.34	−0.62	−0.72	202	53	88
19:00-19:30	1.12	−1.52	−0.29	6.80	−1.52	−0.48	−1.04	206	42	71
19:30-20:00	0.65	−1.17	−0.62	5.00	−1.21	−0.33	−0.88	160	36	63
20:00-20:30	0.39	−1.02	−0.70	6.02	−0.95	−0.15	−0.80	198	32	57
20:30-21:00	0.62	−0.92	−0.87	3.87	−0.90	−0.18	−0.72	219	41	72
21:00-21:30	0.98	−0.85	−0.99	3.67	−1.05	−0.18	−0.87	229	46	79
21:30-22:00	2.15	−0.67	0.24	3.19	−0.97	−0.14	−0.83	228	70	117
22:00-22:30	1.64	−0.54	0.29	5.27	−0.79	−0.11	−0.68	235	56	99
22:30-23:00	1.82	−0.79	0.37	3.17	−0.75	−0.07	−0.68	192	55	92
23:00-23:30	1.52	−0.75	0.50	−0.20	−0.82	−0.07	−0.75	226	73	127
23:30-24:00	3.06	−0.83	0.44	0.87	−0.75	0.00	−0.75	275	83	139

quantities over bare soil at Shionomisaki, 14th July 1972.

Deviations		Friction Velocity	Drag Coefficient at 1.9 m	Air Temperature	Temperature Gradient	Water Vapor Pressure	Water Vapor Pressure Gradient	Bowen Ratio	Soil Temperatures		
σ_w	σ_t	u_*	$C_d\times10^{-2}$	T_{56}	$T_{15}-T_{56}$	e_{56}	$e_{16}-e_{56}$	(Estimated from gradients)	−1 cm θ_{-1}	−2 cm θ_{-2}	−4 cm θ_{-4}
(cm/sec)	(°C)	(cm/sec)		(°C)	(°C)	(mb)	(mb)		(°C)	(°C)	(°C)
12	0.16	10	2.30	25.1	−0.1	30.6	−0.2	0.56	25.6	25.8	26.3
10	0.07	7	0.78	25.1	−0.1	30.4	−0.2	0.56	25.3	25.5	26.1
10	0.14	9	1.67	25.0	−0.1	30.4	−0.2	0.56	25.2	25.3	26.0
10	0.23	9	1.86	24.8	−0.1	30.0	−0.2	0.56	25.1	25.2	25.9
12	0.18	7	0.67	24.8	−0.1	30.1	0.5	−0.13	25.0	25.0	25.7
19	0.13	15	3.85	24.6	−0.1	30.2	0.5	−0.13	24.8	24.9	25.6
15	0.14	10	1.72	24.4	−0.1	29.8	0.6	−0.11	24.6	24.7	25.4
19	0.13	17	3.60	24.3	−0.1	29.9	0.3	−0.22	24.6	24.6	25.3
27	0.13	23	5.11	24.3	0.1	29.4	0.4	0.17	24.3	24.5	25.2
36	0.15	42	2.45	24.2	0.1	29.5	0.1	0.67	24.2	24.5	25.1
28	0.16	20	2.45	24.2	0.1	29.9	0.2	0.34	24.1	24.2	25.0
33	0.16	26	3.41	24.2	0.2	29.7	0.4	0.34	24.2	24.3	24.9
37	0.12	40	4.46	24.3	0.2	29.9	0.4	0.34	24.5	24.6	25.2
33	0.39	22	1.36	24.5	0.4	30.7	0.4	0.67	24.8	24.8	25.4
32	0.34	20	1.10	25.3	0.5	32.2	0.7	0.48	25.6	25.1	25.6
37	0.28	24	1.61	26.0	0.2	33.1	0.9	0.15	26.6	25.6	25.8
30	0.41	16	0.70	27.3	0.5	32.2	1.3	0.26	27.5	26.2	26.3
40	0.48	32	5.03	28.0	0.7	31.7	1.2	0.39	28.8	27.3	27.0
45	0.55	29	3.58	28.9	0.8	32.2	1.0	0.54	30.1	28.2	27.7
59	0.49	31	4.52	29.2	0.9	32.8	1.6	0.38	31.6	29.3	28.4
67	0.44	43	3.25	29.0	1.0	32.9	1.6	0.42	32.4	30.1	29.4
60	0.41	46	3.40	29.2	1.0	33.1	1.5	0.45	33.7	31.0	29.8
53	0.78	39	3.03	29.3	1.0	33.0	2.1	0.32	34.7	31.8	30.5
55	0.55	36	3.09	29.2	1.1	33.9	1.8	0.41	35.5	32.6	31.4
63	0.42	46	4.77	29.2	1.1	32.0	1.7	0.43	35.8	33.1	31.7
53	0.48	35	2.06	29.4	0.9	33.8	1.9	0.32	36.1	33.3	32.2
66	0.46	53	4.81	29.0	0.9	32.4	1.9	0.32	36.3	33.5	32.5
69	0.45	51	4.81	29.4	0.8	31.9	1.6	0.34	36.2	33.6	32.7
71	0.52	56	6.34	29.3	0.8	32.2	1.9	0.28	35.8	33.4	32.9
65	0.40	55	8.26	28.8	0.7	32.0	2.3	0.20	35.4	33.3	32.8
64	0.42	49	4.23	28.9	0.5	32.5	1.9	0.18	34.6	32.7	32.6
64	0.41	50	6.48	28.8	0.4	31.5	1.8	0.15	33.9	32.4	32.4
63	0.22	50	7.29	28.5	0.3	28.6	2.6	0.08	32.5	31.6	32.0
63	0.20	46	5.16	27.4	0.1	28.8	2.2	0.03	31.5	30.8	31.4
54	0.34	41	4.36	27.0	0.4	28.1	2.3	0.12	30.1	30.0	30.5
51	0.45	30	2.35	26.5	0.3	26.9	1.6	0.13	29.3	29.3	29.8
45	0.40	39	4.63	26.2	0.1	26.2	1.4	0.05	28.7	28.7	29.3
50	0.07	33	2.70	25.3	0.0	25.8	0.7	0.00	27.7	27.7	28.6
41	0.10	31	2.20	24.9	0.0	26.1	1.0	0.00	27.0	27.1	28.2
33	0.11	23	2.12	24.5	0.0	25.7	1.4	0.00	26.4	26.5	27.4
28	0.16	18	0.83	24.7	−0.2	25.1	0.9	−0.15	26.1	26.1	27.1
37	0.08	22	1.08	25.0	−0.2	24.4	0.8	−0.17	26.0	26.0	26.9
48	0.15	29	1.56	25.0	−0.2	24.2	0.9	−0.15	25.6	25.6	26.7
55	0.26	42	3.45	25.2	−0.2	24.3	0.8	−0.17	25.5	25.4	26.5
46	0.14	37	2.47	25.2	−0.2	24.8	0.8	−0.17	25.2	25.2	26.1
48	0.07	39	4.11	25.2	−0.1	24.5	0.5	−0.13	25.2	25.2	26.1
54	0.10	36	2.48	25.1	−0.1	24.6	0.5	−0.13	25.0	25.1	25.9
74	0.12	50	3.37	24.8	−0.1	25.2	0.6	−0.11	25.0	25.1	25.9

as explained before

$$Q_G=-k\left(\frac{\partial\theta}{\partial z}\right)_{z=Z}+\int_0^z c\rho\left(\frac{\partial\theta}{\partial t}\right)dz$$
$$\simeq-k\left(\frac{\Delta\theta}{\Delta_z}\right)_{z=Z}+c\rho\left(\frac{\delta\theta}{\delta t}\right)_{z=\frac{Z}{2}}Z \tag{3}$$

where k is thermal conductivity of the soil, θ ground temperature ($c\rho$) being heat capacity of soil per unit volume. In the present experiment the depth of the skin layer, Z was chosen to be 2 cm, and soil temperature, θ was measured with thermocouples at the depths of 1, 2 and 4 cm. The temperature gradient at $Z=-2$ cm is computed by the following relation

$$\left(\frac{\Delta\theta}{\Delta z}\right)_{z=-2}=\frac{\theta_{z=-1}-(\theta_{z=-2}+\theta_{z=-4})/2}{2} \tag{4}$$

and the rate of time change of ground temperature in the skin layer of 2 cm thick is represented by $(\theta_{t+30\mathrm{min}}-\theta_{t-30\mathrm{min}})_{z=1\mathrm{cm}}/60$ min. The thermal conductivity of soil, k is not constant with time, depending on moisture content and is measured by the use of the thermal conductivity probe developed by one of the present authors (Kawanishi, 1964[8]) buried at the depth of 2 cm in the ground. While heat capacity of soil was determined by the calorimetric method from the soil sample cored from the depth of 2 cm. Moisture content of soil was also determined from the sample core by the desiccating method. The measurements of soil characteristics were made four times that day, the results of which are shown in Table 1.

In order to check the heat balance method of turbulent fluxes estimate, the mean air temperature and humidity gradient in the height range between 15 and 55 cm from the ground were measured with the aspirated thermocouple psychrometer with large time constants. The Bowen ratio, R can be estimated as follows, assuming the eddy diffusivities of sensible heat and water vapor are the same,

$$R=\left(C_pK_H\frac{\partial T}{\partial z}\right)\Big/\left(LK_E\frac{\partial q}{\partial z}\right)$$
$$\simeq C_p\Delta T/L\Delta q. \tag{5}$$

This indirectly estimated Bowen ratio can be compared with that obtained directly by the eddy correlation method.

The results of the observation thus obtained are shown in Table 2 together with related parameters. In the computation process of soil heat conduction, smoothed values of physical parameters shown in Table 1 were applied.

3. Discussions

The total values of the independently observed components of the energy fluxes shown in Table 2, which are the total energy exchanges on the bare soil surface on a fine summer day, are as follows

$Q_N=406$ ly/day
$Q_H=76$ ly/day

$Q_E = 212$ ly/day
$Q_G = 107$ ly/day

The residure is only 8 ly/day when applied to the balance equation (Eq. 1). This shows that the energy fluxes are balanced in one day time base even if the fluxes are measured at a short distance from the interface as explained before.

Table 3 shows the two hourly values of fluxes computed from the results of Table 2, and the time changes of these values are also shown in Fig. 1. As is clearly seen from these, the energy fluxes are not balanced at every time interval and the residues shown in the middle column are often as large as 25 ly per 2 hours. Of course, much large relative magnitude of residues is seen in the 30 min base energy balance shown in Table 2.

This shows that the simplified energy balance equation as evaluated by the method shown in the previous section does not hold good at a short time interval even if it is satisfied on the one day time base. The cause of this discrepancy may be the error in the estimation of the rate of time change of heat storage in the skin layer of the ground, because the daily sum of the error is quite small. The heat storage in the skin layer was assumed to be represented by the soil temperature at the middle depth of the skin layer. However, the soil temperature near the interface might be much higher in daytime and much lower in nighttime. As the surface temperature measurement by a radiation thermometer was not made in the present experiment, the above hypothesis cannot be verified. However, it is supported by the fact that the sign of the residue changes at the time when the soil temperature of the skin layer ($Z = -1$ cm) shows the extreme value. If so, the excess heat stored in the daytime, which is about 90 ly, may cause an extremely large amplitude of surface temperature change in the

Table 3. Time changes of two hourly fluxes over bare soil at Shionomisaki, July 14, 1972.

Time	Observed energy fluxes				Residure	Bowen ratio		Heat balance method		
	Q_N	Q_H	Q_E	Q_G	$Q_N-(Q_H+Q_E+Q_G)$	Obs.	Est.	Q_N-Q_G	Q_H'	Q_E'
	ly	ly	ly	ly	ly			ly	ly	ly
00:00-02:00	−10	−3	3	−7	−3	−0.95	0.34	−3	−1	−2
02:00-04:00	−10	−2	−1	−6	−1	−1.88	−0.13	−4	1	−5
04:00-06:00	−5	−2	1	−7	3	−1.91	0.34	2	1	1
06:00-08:00	32	2	8	3	19	0.28	0.34	29	7	22
08:00-10:00	82	20	11	32	19	1.89	0.34	50	13	37
10:00-12:00	116	24	−5	47	50	−5.25	0.37	69	19	50
12:00-14:00	113	17	26	45	25	0.64	0.34	68	17	51
14:00-16:00	82	18	41	25	−2	0.43	0.19	57	9	48
16:00-18:00	25	3	47	−3	−22	0.06	0.10	28	3	25
18:00-20:00	−8	3	34	−9	−36	0.09	0.00	1	0	1
20:00-22:00	−6	−4	30	−7	−25	−0.14	−0.17	1	0	1
22:00-24:00	−5	3	17	−6	−19	0.18	−0.13	1	0	1
Total	406	79	212	107	8	0.37	0.16	299	69	230

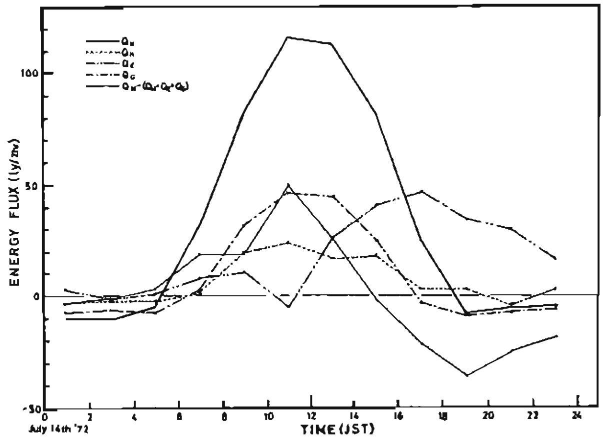

Fig. 1. Time changes of energy fluxes over bare soil on a fine day.

day. More detailed study of the structure of the interface is required.

The another point to be mentioned is the relatively large upward latent heat flux in the evening from 14:00–22:00 in spite of small net radiative energy supply. This may also be caused by saturation of water vapor in the gap of the soil particles in the skin layer of the ground owing to the rapid temperature decrease mentioned above. To explain these results we must have a new model of the detailed structure of air-ground interface.

As the direct measurement of turbulent sensible and latent heat fluxes requires the special instrumentations as shown in this paper to have good results, the simplified method of flux estimation still has significance. For example, if the net radiation and heat transfer into the ground can be measured, the sum of sensible and latent heat fluxes can be estimated from the energy balance equation and sensible heat flux and latent heat flux can be separated by the aid of Bowen ratio, if its value is estimated. This is the principle of the heat balance method.

As is seen from the results of the present experiment, we can estimate the sum of heat fluxes in one day with fairly good accuracy. However, separation of two kind of heat fluxes are troublesome because the mean Bowen ratio throughout the day has no meaning. For this purpose, the sums of the sensible and latent heat flux estimates obtained on a two hourly time base neglecting the existence of the residue mentioned above, give relatively good results as shown in Table 3. However, the flux estimates at each time interval are not so consistent with the observed results, and in the case of negative Bowen ratios the estimates are sometimes different even in the sign from those of the gradients. Of course, in such cases the amount of the flux itself is relatively small and gives no serious effect on the daily sum. For a shorter time interval, such as 30 min, the errors of this method increases as is easily seen in Table 2.

The detailed discussions and conclusions on the energy budget at the air-ground interface will be made after sucessive experiments on this subject.

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